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^{238}U-^{230}Th dating of a geomagnetic excursion in Quaternary basalts of the Albuquerque Volcanoes Field, New Mexico (USA)

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Abstract. We report the ^{238}U-^{230}Th age derived from samples from three basalt flows from the Albuquerque Volcanoes Field, central New Mexico (USA), interpreted to have erupted during one of the Bruhnes Chron geomagnetic field polarity events. Whole-rock samples and magnetite separates from two of the samples define an isochron with an age of 156 ± 29 ka (2σ). It is now possible to determine the ages of geomagnetic excursions with reasonable precision, by the ^{238}U-^{230}Th method, using basalts erupted between possibly 25 and up to 250 ka. Although a strict correlation of the polarity event recorded by the Albuquerque lavas with other high amplitude field phenomena in the latest Quaternary is not yet possible, the Blake and the less well-documented Old Crow and Biwa I/ Jamaica events are likely candidates.

Introduction

Several high-amplitude magnetic field excursions, or polarity events, have been recognized during the Brunhes Chron. However, the ages of many of these features are not accurately known and the correlation of such possibly global events at different locations is problematic. The general difficulty of establishing a magnetic field chronology related to an absolute time scale is well-recognized (Harland, 1990). The reliable dating of polarity events within the last 250 ka using radioactive parent-daughter systems has also proven technically difficult. Geomagnetic records from sedimentary sequences in either marine or continental environments cannot yet be tied to an absolute chronometer except within the ^{14}C timescale (<50 ka), or by $^{40}Ar/^{39}Ar$-based tephrachronology. Ages of some deep sea sediment cores can be inferred from correlations with the marine $\delta^{18}O$ stratigraphy. High-precision absolute ages of terrestrial volcanic sequences, if recording well-defined and correlated excursion/polarity events, could be used to fix some absolute time points on the more extensive marine record and the associated $\delta^{18}O$ stratigraphy or eustatic sea level changes. However, because high amplitude magnetic excursions appear to be of short duration, the chances of finding a lava flow whose eruption coincided with such an event are small, and only a few examples within the last 250 ka are known.

In this study, we have investigated the extent to which the ^{238}U-^{230}Th system, using high abundance sensitivity thermal ionization mass spectrometry (HAS-TIMS), can be used for dating a well-defined field excursion. For internal isochrons, the ^{238}U-^{230}Th chronometer requires a rock and its constituent mineral phases to have the same initial value of $^{230}Th/^{232}Th$ at the time of extrusion and also to have a wide spread in $^{238}U/^{232}Th$ ratios (*e.g.*, Condomines *et al.*, 1982). High concentrations of U and Th in magnetite in basalts have been widely recognized and were used for U, Th-He dating (Hurley, 1954). Using α-spectrometry, Condomines (1978) demonstrated that magnetite can show substantial U/Th fractionation and measured a magnetite-whole rock isochron age of 39±12 (2σ) ka for the Olby basalt flow recording the Laschamp event. However, U/Th fractionation in magnetite is often less than 15% and in some cases is negligible (<1%, Chen *et al.*, unpublished data). The crystal chemical basis for the high U and Th concentrations in magnetite or in inclusions in the magnetite is unknown. As a result, there is no *a priori* basis for anticipating U/Th fractionation in "magnetite" and hence, the usefulness of this phase for obtaining a U-Th isochron is not guaranteed.

Albuquerque Volcanoes Field, New Mexico

The Albuquerque Volcanoes Field is one of several small volcanic centers of Pliocene-Pleistocene age in the Albuquerque-Belen Basin (Fig. 1), part of the Rio Grande rift. This field consists of at least six major lava flows, erupted from a linear chain of cinder cones and several smaller vents. The lavas are olivine tholeiites and contain 3-5% olivine phenocrysts (0.2-2.0 mm) and 3-10% plagioclase phenocrysts (0.5-2.0 mm), in an intergranular groundmass of plagioclase, olivine, augite, Fe-Ti oxides, and interstitial glass. Geissman *et al.* (1989) and Geissman *et al.* (1990) showed that flows of the Albuquerque Volcanoes recorded an anomalous field direction which they interpreted as representing a part of a single polarity event. The basis for this interpretation was that all flows yielded statistically indistinguishable directions, consistent with the very short duration of magmatic activity inferred on the basis of the distinct absence of either palaeosols or aeolian deposits between flows.

Analytical Techniques

We analyzed high quality mineral separates of magnetite and plagioclase, and whole rock samples from three flows (Fig. 1), spanning most of the magmatic activity. Samples were dissolved using HF - $HClO_4$, followed by HNO_3 and HCl. Sample solutions were appropriately spiked with a ^{229}Th tracer and a mixed ^{236}U-^{233}U tracer, to yield $^{229}Th/^{230}Th \approx 50$

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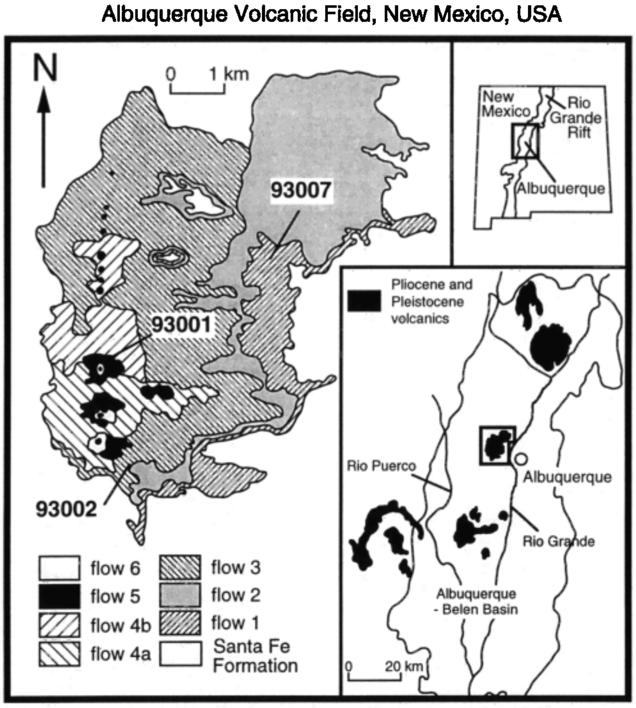

Figure 1. Map of the Albuquerque Volcanoes Field (AVF), New Mexico, USA [after Kelley and Kudo, 1978], and sample localities (93-001, 93-002 and 93-007).

and $^{236}U/^{234}U \approx 10$, in order to measure the ^{230}Th and ^{234}U concentrations. A small aliquot of each solution was spiked with additional ^{229}Th and ^{236}U - ^{233}U to determine the ^{232}Th and ^{238}U concentrations. The procedure used for U and Th separation follows Chen *et al.* (1986). U and Th were initially coprecipitated with $Fe(OH)_2$, using NH_4OH, and then separated and purified by anion-exchange chromatography. Total procedural blanks were in the range of 20 pg for Th and 15 pg for U and are negligible. ^{232}Th and ^{238}U concentrations and $^{234}U/^{238}U$ ratios were measured on the Lunatic I mass spectrometer following the method described by Chen *et al.* (1986), except that the secondary electron multiplier was used in the ion-counting mode. In this study, for $^{230}Th/^{232}Th$ measurements, we utilized a high abundance sensitivity mass spectrometer that was jointly developed by us and Finnigan-MAT (Papanastassiou *et al.*, 1991). The original instrument retarding potential (RP) filter 2nd stage has been substantially modified by us. The abundance sensitivity using the redesigned RP filter is 4×10^{-9} for 1 amu below mass 232 (I_{231}/I_{232}) and 5×10^{-10} at 1.5 amu below mass 232 ($I_{230.5}/I_{232}$). With an additional RF quadrupole (Q) filter, the abundance sensitivity is 4×10^{-10} at 1 amu below ^{238}U or ^{232}Th, and 6×10^{-11} at 1.5 amu difference. Both the RP and RPQ sysems have a transmission of ~50% which yields a total transmission (first and second stages) of 18%. We can reliably measure $^{234}U/^{238}U$ of enriched standards, with ratios of 10^{-6} to 10^{-8} to 1 % and 4 % (2σ), respectively (Papanastassiou *et al.*, 1991). All measurements reported here were made using the RP filter without the RF quadrupole filter. The contribution of the low mass tail of the ^{232}Th peak to the ^{230}Th peak was <1‰ of the ^{230}Th signal. Approximately 500ng of Th were loaded in dilute HNO_3 onto the side filament of a Re double filament assembly; the ionization efficiency for Th was $\sim1\times10^{-4}$. The $^{230}Th/^{229}Th$ ratio was measured in a peak jumping mode, using the second (RP) stage ion-counting system. The correction to $^{230}Th/^{232}Th$ from the small amount of ^{230}Th present in the ^{229}Th tracer solution was ≈2 ‰. The $^{230}Th/^{232}Th$ ratio was calculated from the individual ^{230}Th and ^{232}Th concentration measurements.

The results on a rock standard (Table Mountain Latite, Table 1) are in general agreement with those reported by other laboratories. The precision for the $^{230}Th/^{232}Th$ ratio is better than 1% ($2\sigma_m$). All uncertainties quoted here, including those data from the literature are given as $\pm2\sigma_m$.

Results and Discussion

All samples have ($^{234}U/^{238}U$) activity ratios within 1% of secular equilibrium, indicating no disturbance of the ^{234}U-^{238}U system (Table 1). Ratios of activities for two isotopes will be indicated by enclosing the corresponding isotope ratio in parentheses. For sample 93-001, the youngest flow, the whole rock (WR-1) lies within error of the equiline in a ($^{238}U/^{232}Th$) *vs.* ($^{230}Th/^{232}Th$) activity diagram, see Fig. 2 (*cf* Allègre, 1968) and the magnetite separate (typical grain size of ~50 μm, MAG-1) plots to the right of the equiline. The ($^{238}U/^{232}Th$) value of the magnetite is 37% higher than the whole rock value (1.949 *vs.* 1.423) and gives high *apparent* partition coefficients with $D^{mag/melt}$ of 0.56 for U and 0.41 for Th. The plagioclase separate shows a more extreme U/Th fractionation with ($^{238}U/^{232}Th$) of 2.40, 69% higher than the whole rock value. The plagioclase has an extremely low Th

Table 1. U and Th isotopic data for whole rock samples and groundmass magnetite separates from basalt flows of the Albuquerque Volcanic Field, New Mexico, USA.

Samples		^{238}U (10^{-9} mol/g)	$\delta^{234}U^{\#}$ ‰	^{232}Th (10^{-9} mol/g)	^{230}Th (10^{-15} mol/g)	($^{238}U/^{232}Th$)** Activity	($^{230}Th/^{232}Th$)** Activity
93-007	whole rock	2.507±0.006	+6±4	6.101±0.010	43.4±0.4	1.289±0.004	1.322±0.011
flow 1	magnetite	3.226±0.009		9.621±0.006	58.5±0.6	1.051±0.003	1.130±0.011
93-002	whole rock	2.311±0.004	+5±5	5.370±0.007	40.0±0.3	1.349±0.003	1.383±0.009
flow 3							
93-001	whole rock	2.628±0.004	+8±5	5.790±0.009	44.5±0.6	1.423±0.003	1.427±0.020
flow 6	leached WR	2.252±0.003		4.804±0.009	35.8±0.3	1.47±0.003	1.383±0.01
	magnetite	1.467±0.002	-4±7	2.360±0.003	23.1±0.3	1.949±0.003	1.819±0.024
	plagioclase	0.0389±0.0001	-	0.0508±0.0002	-	2.403±0.010	-
TML^{++}	whole rock	45.13±0.37	-	132.0±1.2	760±3	1.072±0.004	1.073±0.010

$^{\#}\delta^{234}U = 1000\times\{([^{234}U/^{238}U]_{sample}/[^{234}U/^{238}U]_{eq})-1\}$, where $[^{234}U/^{238}U]_{eq}$ is the atomic ratio at secular equilibrium and is equal to 5.472×10^{-5}. We obtained $\delta^{234}U = -34\pm3$ (n=5) for the NBS960 U standard during this study; *cf* $\delta^{234}U = -37\pm2$ (Chen *et al.*, 1986). **Parentheses denote activity ratios. ++Table Mountain Latite, a rock standard (*cf* Williams *et al.*, 1992), average of 4 analyses on 90 to 240 mg samples. All errors are 2 σ.

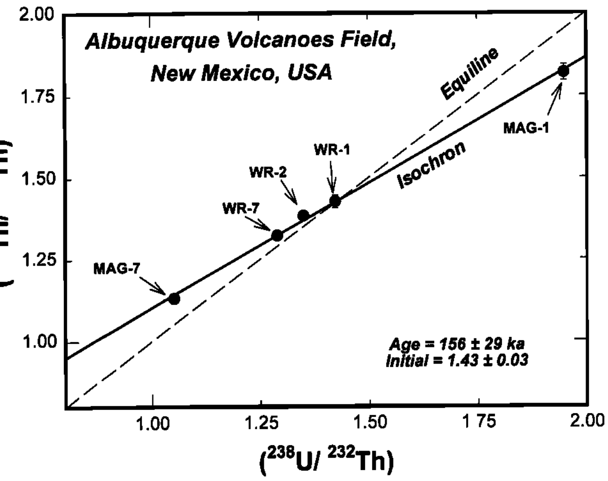

Figure 2. ($^{230}Th/^{232}Th$) *vs.* ($^{238}U/^{232}Th$) plot for the Albuquerque samples. All samples (WR-7, MAG-7, WR-1, and WR-2) except MAG-1, plot to the left of the equiline. An isochron through all samples yields an age of 156±29 ka and an initial ($^{230}Th/^{232}Th$) value of 1.43±0.03.

content (0.012 ppm), implying an apparent $D^{plag/melt} = 0.009$ for Th. The concentration of ^{230}Th in the plagioclase was not measured. For sample 93-007 (the oldest flow), the whole rock (WR-7) and magnetite (MAG-7) plot to the left of the equiline. However, the magnetite has a significantly lower ($^{238}U/^{232}Th$) than the whole rock, in marked contrast to the high ($^{238}U/^{232}Th$) relative to the whole rock found in the magnetite from sample 93-001. This magnetite fraction, MAG-7 also gives high *apparent* $D^{mag/melt}$>1 for Th and U. It is evident that the U/Th fractionation and the U and Th concentrations found in "magnetite" populations is not simply due to crystal-melt fractionation but must reflect the presence of occluded phases that are fractionated.

The whole rock-magnetite pairs for 93-001 and 93-007 give isochron ages of 149±28 (2σ) and 180±49 (2σ) ka, respectively (λ_{230}=9.195x10^{-6} yr^{-1}). A whole rock sample (WR-2) from an intervening flow (93-002) also plots to the left of the equiline, with ($^{238}U/^{232}Th$) between WR-1 and WR-7. Taking all the data together, they are consistent with a single best-fit straight line (Fig. 2), which yields an isochron age of 156±29 ka (2σ). This implies also that all three flows are consistent with the same initial ($^{230}Th/^{232}Th$) (obtained from the intersection with the equiline), which is defined by the isochron as 1.43±0.03 (2σ). We show in Table 1 also the results on a sample of 93-001 which was first leached with 0.5N HCl, for 5 minutes. The results for the leached sample show substantial and differential removal of U and Th (14% and 17%, respectively) relative to the unleached sample. The leached sample falls far off the isochron. This indicates that even mild leaching can adversely affect the U-Th systematics and should be avoided.

For sample 93-001, the whole rock is positioned essentially on the equiline, with ($^{230}Th/^{238}U$) for this sample defining an initial value of 1.012 ± 0.014 and a present day value of 1.003 ± 0.014, showing essentially no U-Th fractionation, at the time of eruption, relative to its source. By contrast, the initial ($^{230}Th/^{238}U$) ratios for the 93-007 and 93-002 flows show marked enrichments in ($^{230}Th/^{238}U$) of about 10% (1.107 for 93-007, and 1.106 for 93-002) relative to secular equilibrium. The whole rock samples also show a significant range in ($^{238}U/^{232}Th$) from 1.29 to 1.42 from the older to the younger flows sampled, with the youngest flow (93-001) at secular equilibrium. Assuming the source of these basalts to be in secular equilibrium, from the initial ($^{230}Th/^{232}Th$) we obtain Th/U in the source of 2.19. The cause of U/Th variation in these basalts or the nature of specific magma chamber fractionation processes are not known. The U/Th fractionation is unlikely to have resulted from fractional crystallization as this would involve primarily olivine and plagioclase, both Th- and U-poor phases. Small differences in the degree of partial melting in the presence of residual garnet could have produced the observed spread in U/Th and the small initial excess of ^{230}Th over ^{238}U (LaTourrette *et al.*, 1993), but the likely effects of crustal contamination must also be considered. Perry *et al.* (1987) measured $^{87}Sr/^{86}Sr$ ratios of 0.7035 and 0.7043 in two of the Albuquerque flows and suggested that this difference was caused by interaction with crustal material.

Whole rock K-Ar dates for the Albuquerque flows reported by Bachman and Mehnert (1978) and Geissman *et al.* (1990) are of low precision because of the low K_2O contents (< 0.5 wt%) and young age. Champion *et al.* (1988) selected two analyses with the highest radiogenic Ar to estimate an age of 182±62 (2σ) ka. Geissman *et al.* (1990) reported an interpreted age of 155 ± 94 (2σ) ka, calculated from a weighted average of five new analyses. Geomorphologic studies of lava flow surfaces in the southwestern United States have shown that the degree of soil development in aeolian deposits on flow surfaces correlates with the age of the underlying lavas. Evaluation of soil profiles on the flow surfaces of the Albuquerque lavas by Geissman *et al.* (1990) suggested an eruption age between about 80 and 250 ka. The ^{230}Th-^{238}U isochron age determination for the Albuquerque Volcanoes field, presented here, is consistent with these estimates but represents a significant improvement in precision. Although the geochemical reason for U/Th fractionation in magnetite is not understood, we conclude that the ^{230}Th - ^{238}U chronometer can be used to determine ages precisely. The same experimental range in $^{238}U/^{232}Th$ at an age of 30 ka, with the same precision in measurement, would yield an uncertainty of ±2.5 ka; at an age of 250 ka, the uncertainty in age is amplified and would be +110/-54 ka, reflecting the relatively short half-life of ^{230}Th (75.4 ka). Higher precision at 250 ka will require a much larger spread in $^{238}U/^{232}Th$. It follows that this chronometer may have a wide applicability in determining ages of volcanic rocks in the age range from 25 ka up to around 250 ka.

The more precise Th-U isochron determination for the age of the Albuquerque volcanoes helps to increase the reliability of the correlation of the polarity event recorded by these rocks with other known or inferred polarity events. Permissible correlations of the Albuquerque Volcanoes feature are with what Nowaczyk *et al.* (1994) categorized as the "Blake" (e.g., Tric *et al.*, 1991), "Baffin Bay" (Aksu, 1983) and "Biwa I" (Kawai *et al.*, 1972) events. The Blake event has been exceptionally well-defined and has an estimated age between about 110 and 135 ka. For the Biwa I event, Nowaczyk *et al.* (1994) included records of the Jamaica feature (Ryan, 1972), the second youngest feature at Lake Biwa, Japan (Kawai *et al.*, 1972) and from the Fram Strait where it was assigned an age range of 171 to 181 ka by Nowaczyk and Baumann (1992) based on ^{10}Be, ^{230}Th and $\delta^{18}O$ data. Champion *et al.* (1988) preferred to call this the "Jamaica" event. For the Baffin Bay event, Nowaczyk *et al.* (1994) included records from Baffin Bay (Aksu, 1983), Fram Strait (Nowaczyk and Baumann, 1992) and Alaska (the "Old Crow" feature first reported by Westgate *et al.*, 1985). However, the Baffin Bay record has been reinterpreted to be less than about 40 ka (*e.g.*, De Vernal *et al.*, 1987). Hence, if there is a polarity feature between the Blake and Biwa I events then the most permissible evidence for it comes from the Old Crow record, and the name "Baffin Bay" for this event should be replaced. Age estimates for the Old Crow feature, recorded in tephra deposits, range from about

140 ka to 170 ka. Glass from the tephra has been dated by fission tracks (149 ± 26 ka, Westgate, 1988) and thermoluminescence (170 ± 27 ka, Berger *et al.*, 1992), and loess deposits 10 cm above and 60 cm below the Old Crow tephra give thermoluminescence dates of 110 ± 32 ka and 140 ± 30 ka respectively (Berger *et al.*, 1992). Thus, within the error limits of our age determination of the Albuquerque Volcanoes, the high amplitude feature recorded by these lavas may be correlated with either the Blake or Biwa I events, or the Old Crow event if it is distinct from the other two. World-wide correlations of specific high amplitude field phenomena, required to better understand the morphology of the geomagnetic field during extreme departures from normal behavior, can only be made with accurate and high-precision age determinations.

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